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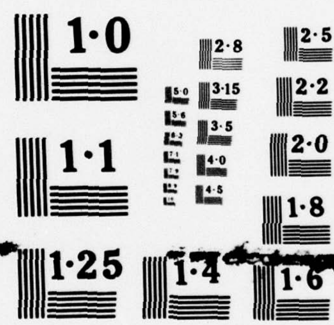

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Interim Scientific Report

PROGRESS REPORT ON ANALYTIC INVESTIGATION OF MULTINOZZLE PLUME FLOW FIELDS

by

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Washington, D.C. 20332

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Multinozzle plume flow fields are of specific interest in many military and civilian programs because the associated observables and vehicle interference effects are directly related to primary system design variables. There is no a priori plume fluid dynamics at present that accounts for the plume-plume impingement effects which arise when more than one engine exhaust is present. The reason for this is that the prediction of these highly complex three-dimensional supersonic flows, which contain several intersecting shock surfaces, is at the edge or beyond the state-of-the-art. The computation of these flow fields has only recently come within the possible realm of computer codes and numerical fluid dynamic prediction techniques. This research effort is aimed at the development of advanced numerical methods and computer codes employing finite difference techniques and discrete floating shocks and boundaries for the prediction of these inviscid flow structures. A parametric study employing an overall model for near field has been employed to show that shock heating due to multinozzle impingement plays a central role in plume observables. It remains for the further development of the computer code presently being devised to predict this near field shock heating from first principles.

Underexpanded plume flow fields can be divided into regions defined by the dominant forces which act on the fluid. In the near field the flow is characteristically inviscid supersonic flow containing infinitesmally thin shock waves. Significant viscous effects are confined to a thin mixing layer separating the exhaust gas from the ambient stream. Shock surfaces and expansion fronts cross and recross the exhaust flow repeatedly over axial distances as large as hundreds of nozzle exit radii until the pressure is equilibrated with ambient. Over approximately the same distance the mixing layer which was thin in the near field has grown to a significant fraction of the exhaust gas and eventually engulfs the entire exhaust gas. In this region, the far field, the flow is dominated by turbulent mixing processes at nearly constant pressure. The fluid temperature levels entering the far field are directly related to the shock heating in the near field as total pressure losses due to the shock waves persist.

The infrared signal emitted by a missile plume is the sum of the radiation from the hot gasses in the entire extent of the flow. In certain situations the bulk of the radiation arises in the far field which is generally substantially larger than the near field. Even though the far field has achieved nearly axisymmetric form and is pressure equilibrated the shock heating arising in the three-dimensional near field is of primary importance in determining the level of radiation from the far field. This is shown rather pointedly in the Appendix (Section 4) where a parametric study indicates that for a certain level of total pressure in the far field the correct spatial distribution of IR radiation can be calculated. The a priori prediction of the total pressure losses (entropy increase) associated with the near field requires the ability to predict the shock wave structure in the near field. The radiation from the near field is directly related to this shock structure through the direct dependence of IR radiation on local temperature levels.

The Appendix herein is a copy of a paper presented at the 10th JANNAF Plume Physics meeting held in San Diego in September 1977. This paper reviews the progress to date on the qualitative description of the multinozzle plume flow fields and the present state of development of the numerical computation techniques and programs being developed. In addition, results of a parametric far-field study indicating the importance of (near field) shock heating as a result of plume-plume impingement are presented. At present the computer code has the capability to predict the impingement of two uniform rectangular plumes. The code is three-dimensional, treats shock surfaces and pressure boundaries as discrete "floating" discontinuities, and contains a detailed model for the interaction of the impingement shock and the constant pressure plume boundary. Details of the numerical technique can be found in Ref. 1 which was presented at the AIAA 10th Fluids and Plasma Dynamics Conference in June 1977.

The next step in the development of the code is the introduction of three-dimensional shock-shock interactions. This is required because in the flow field associated with the impingement of two underexpanded plumes the impingement shock surface intersects the barrel shock surface.

The detailed treatment of this interaction has not been addressed by any previous numerical models of supersonic flows. The two shock surfaces are both of the same "family". That is, when viewed in a coordinate system along the line of intersection, each deflects the flow in the same (rotational) sense. The nature of the shock-shock interactions as brought out by the shock polar diagrams in the pressure hodograph plane indicates that there are three possible limiting cases which determine the ultimate propagation of the shock surfaces. In each case the nature of the interaction changes abruptly as the Mach number relative to the intersection point of the shock surfaces becomes sonic. At the initial intersection of the shock surfaces the subsequent transmitted and reflected waves are determined by conditions ahead of the two incident shock waves. This condition prevails for a short axial distance downstream along the interaction line as long as the Mach number ahead of the incident, reflected and transmitted waves are all supersonic. At some point the relative Mach number becomes subsonic behind one of the shock waves. In each case the subsequent shock structure becomes more complicated and the intersection line itself is no longer determined by the simple geometric intersection of the two incident waves. The proper evaluation of this interaction is one of the subjects of this year's research effort.

A problem that has arisen in the present work is associated with entropy layers that develop in multinozzle plume flow fields. This problem can be briefly described as a subgrid problem for the entropy distribution. The finite difference mesh, which is fine enough to resolve pressure and cross flow angle variations, may not be fine enough to resolve entropy distribution. This occurs because the streamlines (lines of constant entropy) which originate behind the variable strength shock surface tend to accumulate near the edges of the flow and so develop large entropy gradients. Several methods have been employed in the past (Refs. 2 and 3) to relieve this problem. In essence,

streamline tracing is employed on boundary surfaces and windward differencing schemes are employed in the field. These improvements are presently being added to the code.

In summary, progress to date has been achieved in both the development of the three-dimensional code to compute the inviscid structure of the multiple nozzle flow fields and in substantiating the role of near field plume-plume impingement on overall plume IR radiation. The computer code is presently capable of predicting the impingement flow field of two rectangular jets. Papers were presented this year at the 10th JANNAF Plume Physics meeting and the 10th Fluids and Plasma dynamics conference of the AIAA discussing various aspects of the current research effort.

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APPENDIX

MULTINOZZLE PLUME FLOW FIELDS: STRUCTURE AND MODELING*

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ABSTRACT

All present plume models are based on single nozzle flow fields in which an "equivalent" engine is defined that has identical thermodynamic exit plane properties and the combined thrust of all the individual engines. Many vehicles of interest have multiple exhaust nozzles leading to both near and far field flow properties not properly portrayed by this single nozzle concept. Rocket nozzles generally operate at underexpanded conditions so that the individual exhaust plumes impinge creating highly complex flow fields containing a number of three dimensional shock surfaces and shock wave plume boundary interactions. The shock structure of the idealized single equivalent engine is markedly different from the true case implying major differences in both the near and far fields. This paper describes a current research effort which has the goal of devising more realistic models for the flow fields associated with multinozzle exhaust plumes. An advanced three dimensional numerical computation procedure is being developed for the detailed a priori calculation of these flow fields. Initial computations for the impingement of two uniform rectangular plumes are presented. In addition, a parametric study based on a global model of near field shock structure has been performed indicating the importance of multinozzle plume impingement on plume radiation.

1. INTRODUCTION

Detailed knowledge of jet and rocket engine exhaust flow fields is sought in a wide variety of military and civilian programs. The prediction of infrared signature, radar cross-section, and electromagnetic wave attenuation requires the ability to predict the spatial distribution of all thermodynamic and flow quantities, which are dictated by plume fluid mechanics. All present plume models are based on single nozzle flow fields in which an "equivalent" engine is defined that has the combined thrust of all the individual engines. Many vehicles of interest have either multiple engines or multiple exhaust nozzles leading to both

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near and far field flow properties not properly portrayed by the single nozzle concept. Rocket nozzles generally operate at underexpanded conditions so that the individual exhaust plumes spread laterally and impinge. Highly complex flow fields arise containing a number of three dimensional shock surfaces and shock wave plume boundary interactions. This paper describes a current research effort which has made significant steps toward the understanding and prediction of these flows. The flow structure associated with the impingement of two underexpanded rocket plumes is discussed in the next section, and three distinct possibilities appear depending on the strength of the impingement shock wave. The prediction of these complex flow fields requires the development of advanced three dimensional floating shock computational procedures. The method originally devised by Moretti (Ref. 1), an outgrowth of previous fitted shock techniques (e.g., Refs. 2-5), is based on finite difference techniques which allow for many discontinuities in the flow field. In the present work discrete shock waves, pressure boundaries, and more complex singularities are permitted to float in the computational mesh. (See Ref. 6 for more details of the computational procedures.) Initial results employing the new computer code for the flow field associated with the impingement of two uniform rectangular plumes are presented. This flow field demonstrates several interesting features associated with the underexpanded case.

The shock systems which develop in the near field as a result of plume impingement produce entropy increases in the exhaust gases which persist downstream. The temperature levels and hence radiation levels in the far field (pressure equilibrated trail) are thus directly related to the detailed shock structure in the near field. Ultimately the numerical procedures that are being developed will be capable of the prediction of these shock systems and hence entropy levels of the exhaust flow. For timely engineering applications a simple model for the multinozzle plume has been devised wherein all the exhaust gas flow undergoes a uniform entropy increase associated with the near field shock structure. A parametric study employing this model is presented in the following section in which comparison with experimental data is used to determine the entropy level (total pressure) in the far field. Computed station radiation is compared with data for several altitudes. The final section contains conclusions and areas for further study.

2. FLOW FIELD STRUCTURE

The structure of the multinozzle plume flow field contains a complex pattern of shock waves governed by three dimensional considerations. There are three major shock systems in the multinozzle plume flow field. In addition to the expected barrel shock (B shock) which forms in the undisturbed axisymmetric portion of the flow and the impingement shock (I), which forms as a direct result of the collision of the two plume flow fields, a recompression shock surface (R) spreads laterally to increase the pressure as the flow expands below the boundary pressure. The barrel shock forms in the single nozzle plume because expansion waves in the flow reflect from the (near) constant pressure plume interface resulting in reflected compression waves. These eventually focus to start the barrel shock system (B1) (see Fig.1). The expansion waves which start this process generally arise from the conical-like source flow leaving the

nozzle, however, a uniform parallel exit flow nozzle will produce upward running expansion waves because the flow is axisymmetric. The axisymmetric nature of the flow causes the wave strength of the B1 shock to increase as it approaches the axis of the plume and results in a Mach disc and reflected shock system (B2). The flow behind the Mach disc is subsonic so that the location of the disc depends on expansion and mixing processes downstream of it. This is in distinction to the remainder of the flow which is supersonic and where there is no upstream influence. This inviscid flow pattern is well understood and several computer codes are available (in varying degrees of approximation) to predict it (Refs. 5 and 7).

The flow pattern of the multiple nozzle plume has two additional shock wave systems. The shock structure of a uniform twin jet impingement, Fig. 2, is quite informative in the nature of the impingement shock (I) and recompression shock (R) systems. In the side view the I shock appears basically as expected from a two dimensional pattern. A complex process takes place at the intersection of the plume boundary and the I shock. Based on work by Hunt and coworkers (Refs. 8-10) the discontinuous boundary pattern sketched in Fig. 2 is expected. These references deal with normal impingement of uniform jets; however, the interaction of the I shock and the plume boundary is locally equivalent to that case when viewed in a coordinate system parallel to the shock/boundary intersection line. An expansion is required to emanate from the plume boundary at the point of impingement to cancel the pressure rise due to the I shock wave (Station 1). Thus, at the point of impingement the shock must produce at least sonic velocity, relative to the intersection line, to support a Prandlt-Meyer fan. At Station 2, a new feature developes in the flow - expansion wave fronts stretching in three dimensions interact with the constant pressure boundary giving rise to inward moving compression wave surfaces that coalesce to form a recompression (R) shock system. This coalescence is completely analogous to the formation of the barrel shock (B) system in the axisymmetric case. Subsequently, (Station 3-5) the R shock system shrinks in size and grows in strength as it approaches the plume center. Another way of viewing the overall impingement process is to consider that the impingement shock by elevating the pressure of a perfectly matched plume creates an underexpanded jet which subsequently expands giving rise to the shock pattern familiar to underexpanded plumes.

The impingement of two underexpanded plumes, in general, contains the three shock systems discussed above which are further distorted by the spatially non-uniform flow. Many shock configurations are possible depending on the relative strengths of the three systems and the order in which they intersect. Three observed configurations will be discussed. Each flow schematic is followed by a corresponding glow photograph (Ref. 11).

In the weak interaction case (Fig. 3) the flow pattern is initially that of two individual plumes. The first Mach cell is only slightly distorted by the I shock (see top view). The next major shock pattern occurs downstream of the Mach discs in the central portion of the flow between the exit of the two nozzles. The R shocks (side view, Fig. 3) from the upper and lower portion of the flow intersect to form a wedge-shaped shock pattern in the flow. The leading edge of this system is cut off as it is intersected by the reflected barrel shock downstream of the Mach

disc (top view, Fig. 3). At lower background pressures the initial expansion at the nozzle lip is greater and the plumes impinge at higher angles increasing the strength of the impingement shock. Figure 4 is an example of a moderate interaction where the impingement shock strength is increased to the point where it cuts off the barrel shock system before the formation of the Mach disc associated purely with the barrel shock. In this case downstream of the B/R intersection (top view) the R and transmitted B shock intersect in such a way as to create a normal shock (Mach disc) in the center of the flow. In the strong interaction case (Fig. 5) the impingement shock rapidly traverses the plume and diverts the B shock sharply toward the symmetry plane. This transmitted B shock reaches the symmetry plane (top view) at point A while the R shock (side view) is still out near the plume boundary. As the B shock system reflects from the symmetry plane a V shaped trace is created in the side view (Fig. 5). Subsequently this reflected B shock intersects with the R shock surfaces producing an irregular shaped leading edge because both these shock surfaces are not planar (Fig. 5, station 2).

The structure of the multiple nozzle plume impingement flow field indicates that the computational procedure required to analyze this flow field must allow for a wide variety of possible shock configurations and have the flexibility to allow for as yet unknown additional geometries. The "floating discrete shock fitting" approach devised by Moretti was chosen as the preferred approach for the subject problem. Further discussion of the details of this numerical technique can be found in Ref. 6.

3. CALCULATION FOR THE IMPINGEMENT OF UNIFORM RECTANGULAR PLUMES

The initial computation employing the three dimensional floating discontinuity program was for the impingement of two uniform rectangular jets. This was chosen so as to reduce the complexity brought about by nonuniformities in the underexpanded plume while providing a calculation which tests large segments of the new code. The geometry describing the initial calculation is shown in Fig. 6. Two uniform Mach 3.0 plumes of rectangular cross section impinge at 30°. Impingement shocks spread across the plumes (top view) to make the two flows parallel. This results in pressure above the background, and the flow spreads laterally (side view) to relieve this overpressure. The cross-section shown in Fig. 6 is characteristic of the calculated results. The impingement shocks are slightly curved and are bounded by the free jet boundary. The pressure boundaries spread laterally in a vee shaped pattern (which does not violate symmetry because the flow is three dimensional). A typical cross section from the calculation is shown in Fig. 7. (Only one fourth of the total cross section is shown because of the bilateral symmetry.) The flow from the undisturbed plume passes downward through the impingement shock and jumps in pressure. The impingement shock intersects the undisturbed plume boundary in a complex interaction involving a sonic shock condition and a centered Prandtl-Meyer fan (which are all correctly portrayed in the calculation) with the combined result of no pressure change along the pressure boundary. The isobars for this cross section (Fig.7) show that the flow has nearly the undisturbed two dimensional impingement shock value at the centerline (see Fig. 8). The decay to background pressure

takes place across the entire flow and is most rapid in the vicinity of the shock/boundary intersection point. More details are shown in the symmetry plane pressure profile, which is combined with the cross sectional view in Fig. 8 for z = 2.12 (the plume half width is unity). There is a region of near constant pressure developing at the outer fringes of the pressure boundary as would be expected. There are some "wiggles" in the pressure near the edge; however, it appears to be due to the low number of mesh points used in the calculation (see Fig. 7 which includes the exact mesh employed). Figure 9 shows the calculated development of the cross sections of the impingement region as a function of distance downstream of the impingement line. Each profile is ten calculation steps from the previous; the first being at Step 10. The pressure boundary develops into a rather pointed shape. Further computations are necessary to determine if this phenomena is an artifact of mesh spacing and/or initial conditions. An interesting comparison is made in Fig. 10 with calculations reported in Ref. 12. The calculations are for the plume boundary of a scramjet exhaust employing a shock capturing technique. The splitter plate produces impingement shocks similar in geometry to those in the present calculation. The comparison, which is meant to be qualitative, is quite striking in that even the bend in the boundary is reproduced. This gives some confidence in the present results; however, further comparison with other three dimensional flow calculations would be useful.

4. GLOBAL MODEL FOR THE PLUME FAR FIELD

In general, the rocket plume can be divided into two basic regions with respect to the dominant forces which drive the fluid. The pressure at the exit plane is above ambient (underexpanded) giving rise to a series of shock waves and expansion zones which ultimately equilibrate the pressure (Fig. 11a). This comprises the near field which is dominated by a balance of pressure and inertia forces. In the far field (Fig. 11b) (pressure equilibrated trail) the balance is between mixing and inertial forces. Mixing plays a secondary role in the form of a boundary layer in the near field and pressure forces are perturbations in the far field.

Multinozzle plume impingement in the near field gives rise to strong shock waves with their associated entropy jumps (total pressure losses). When the exhaust gases reach the far field these total pressure losses are reflected as temperature levels in excess of an isentropic expansion of the fluid from the exhaust plane to ambient pressure. Thus, the strength of these shock systems in the near field is directly related to far field radiation levels. The detailed calculation procedure (Ref. 5) is aimed at the a priori prediction of these shock systems. To illustrate the importance of multinozzle plume impingement and to gain at least an engineering approach for timely predictions, a simple model of the near and far fields was devised. The near field shock structure is modeled overall as a loss in total pressure of the entire exhaust flow followed by an expansion to ambient pressure. The far field is then calculated employing the LAPP code which is applicable to the constant pressure flow field. The Ting-Libby eddy viscosity transformation is employed in those calculations (Ref. 13). Since the total pressure drop in the near field is not known a parametric study was undertaken. Figure 12 illustrates

the large variation in station radiation associated with various levels of total pressure in the far field. The peak value in station radiation increases by a factor of twenty-three for a ninefold reduction in total pressure.

Figures 12 and 13 compare calculations for two altitudes with experimentally measured station radiation to determine the appropriate total pressure in the far field. The results indicate that substantial total pressure losses must be invoked in order to match the data. Figure 14 shows the total pressure distribution that is achieved in the far field for a single nozzle plume (50 km). The shock wave system associated with the single nozzle flow is far too weak to produce the temperature levels required by the data.

An important factor in these calculations is the chemical model which is assumed for the exhaust gases in the inviscid plume core. For the altitudes shown the gas composition for the expansion to ambient pressure was taken to be frozen. At these altitudes the extremely large pressure ratio from nozzle exit to ambient makes the far field initial temperature a strong function of gas properties. Thus, for example, a perfect fluid expansion, which is commonly employed in all plume models, is very sensitive to the value of γ (the ratio of specific heats) which is chosen for the exhaust gas

$$T/T_e = (p/p_e)^{\frac{\gamma-1}{\gamma}} \, (p_c/p_t)^{\frac{\gamma-1}{\gamma}} \; *$$

The wide temperature range that the gas undergoes expanding in the plume makes the choice of a simple appropriate γ difficult.

5. CONCLUSIONS

The flow field associated with multinozzle plumes is a complex three dimensional problem with a variety of possible configurations. An advanced numerical computational technique is being developed to predict the complex shock patterns associated with these plumes. Initial results for the impingement of two uniform plumes have been attained. After impingement the plumes spread laterally to relieve the over pressure caused by the impingement shock. The entropy wake associated with the near field persists resulting in elevated temperature levels in the far field. A parametric study shows that the shock strength required to match data is far greater than is achieved by a single equivalent nozzle which has the combined thrust of all nozzles with all other flow parameters the same.

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* notation: e = exit plane, t = total pressure in far field, c = chamber pressure

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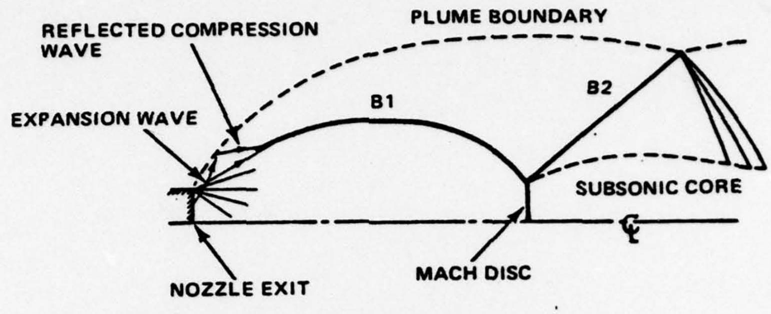

Fig. 1 Single Nozzle Plume Flow Field

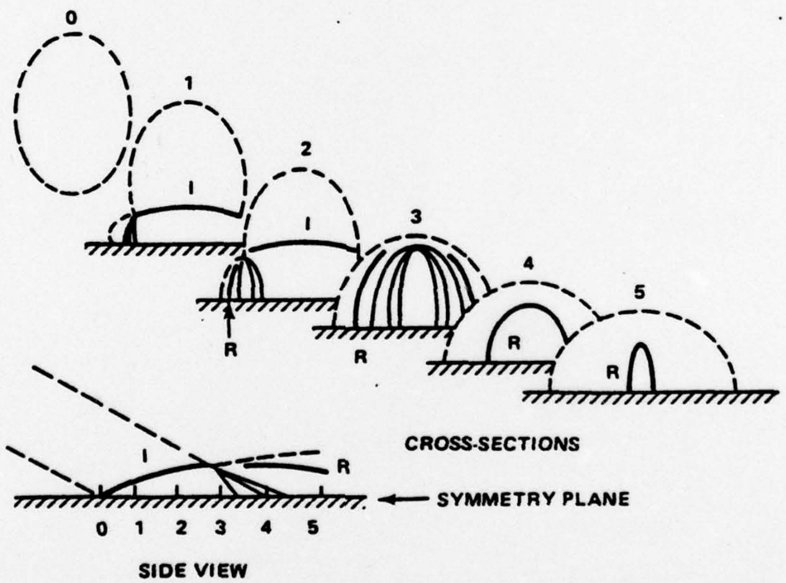

Fig. 2 Impingement of Two Uniform Plumes

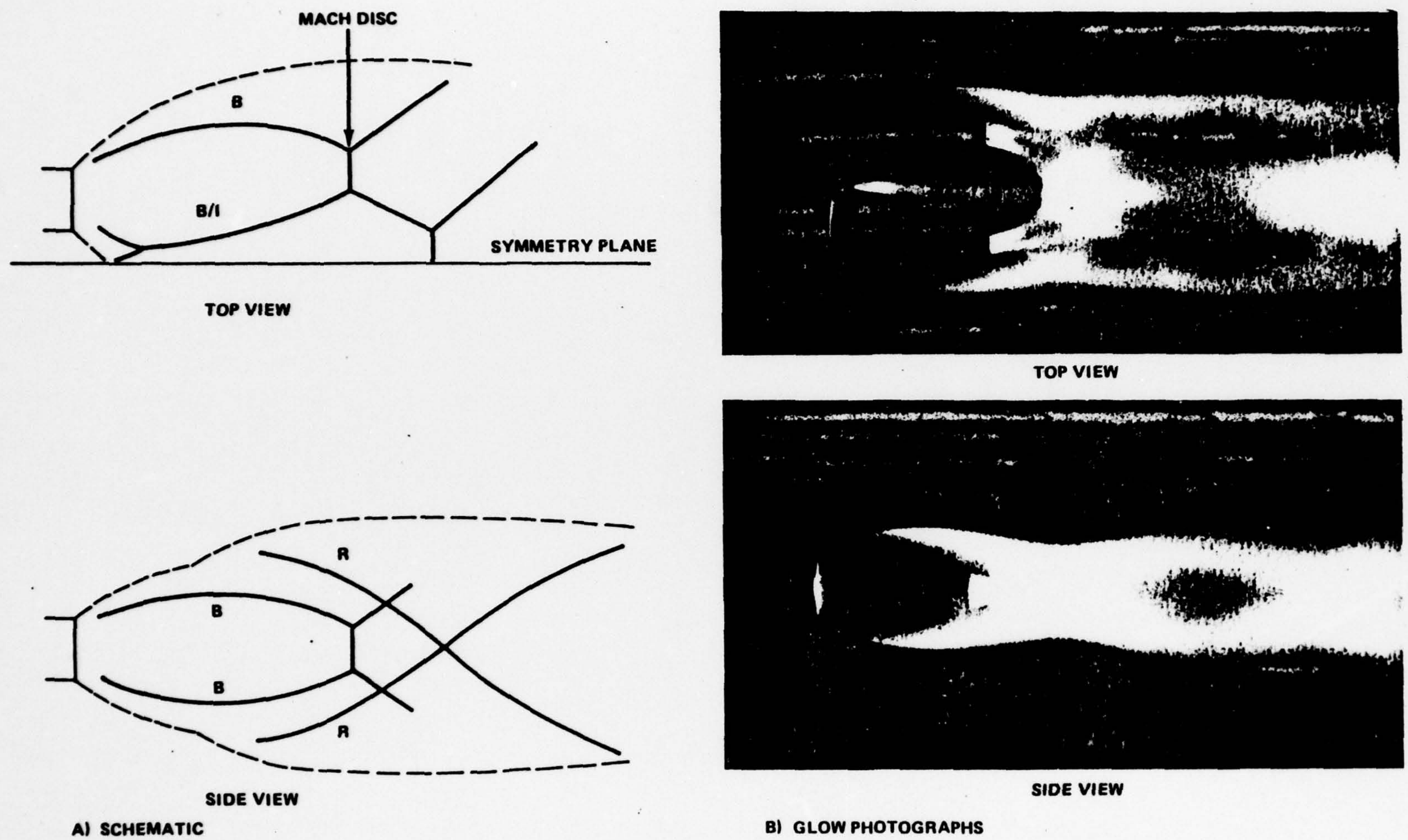

Fig. 3 Flow Pattern Underexpanded Twin Plumes, Weak Interaction

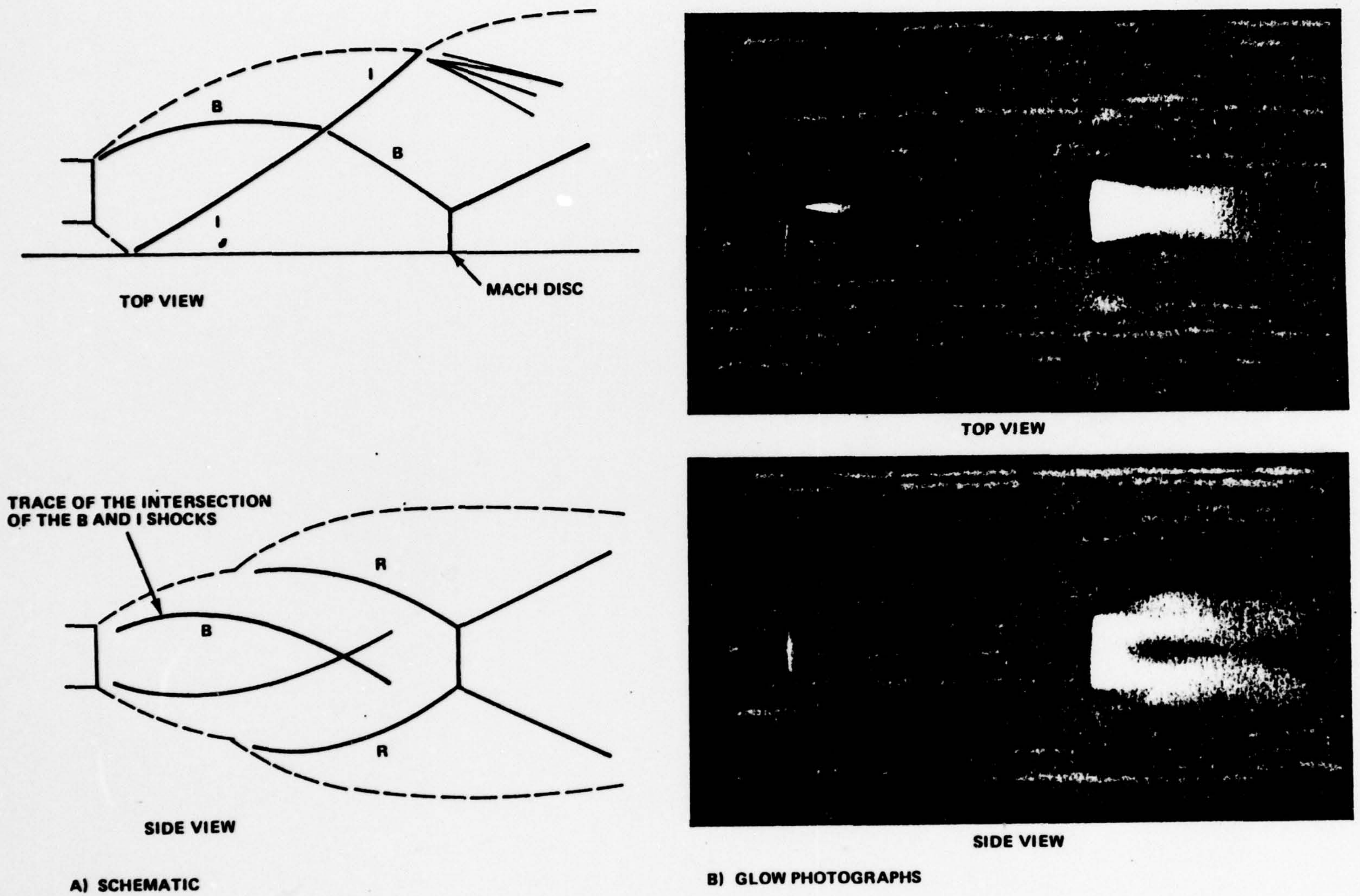

Fig. 4 Flow Pattern of Underexpanded Twin Plumes, Intermediate Interaction

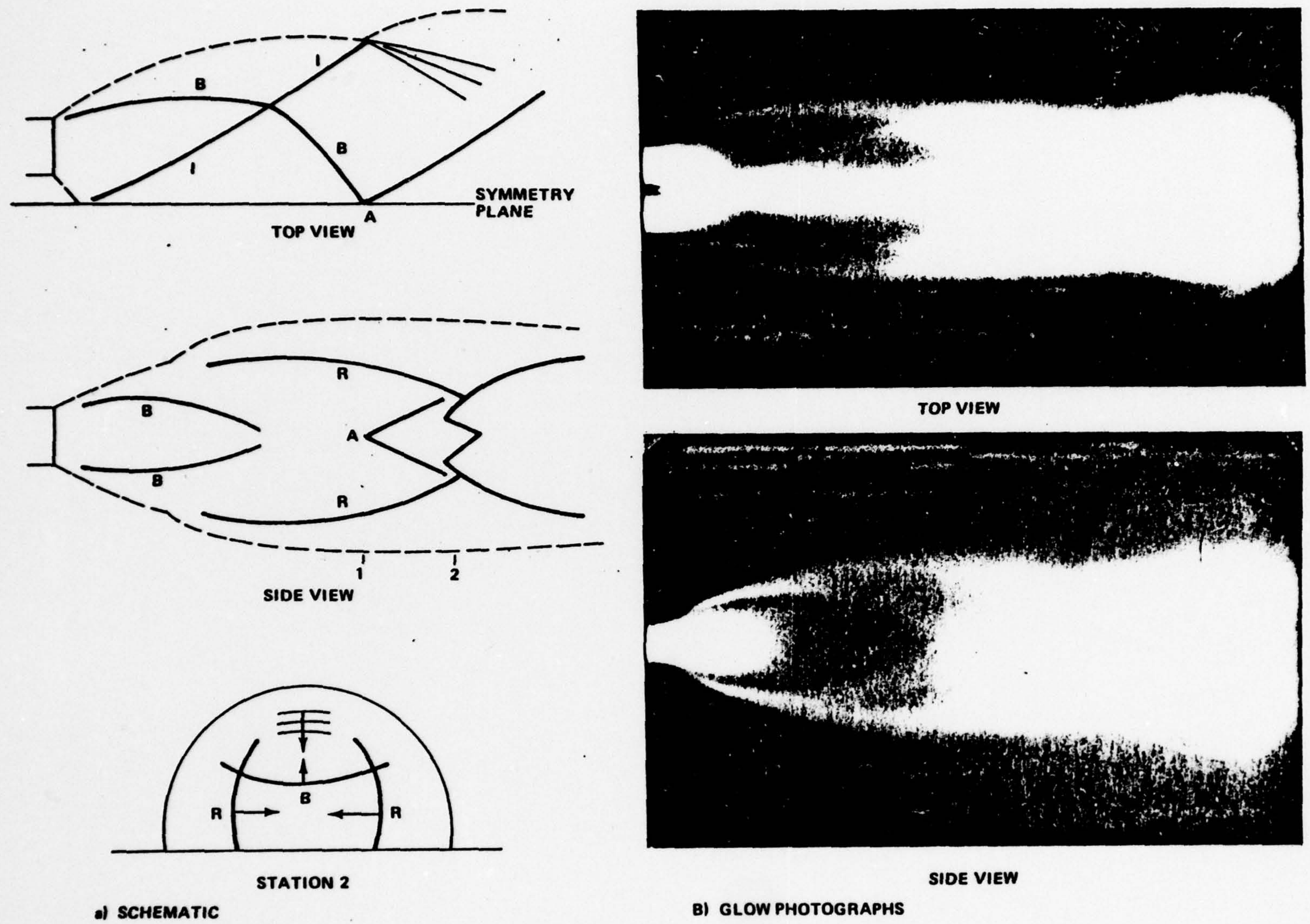

Fig. 5 Flow Pattern Underexpanded Twin Plumes, Strong Interaction

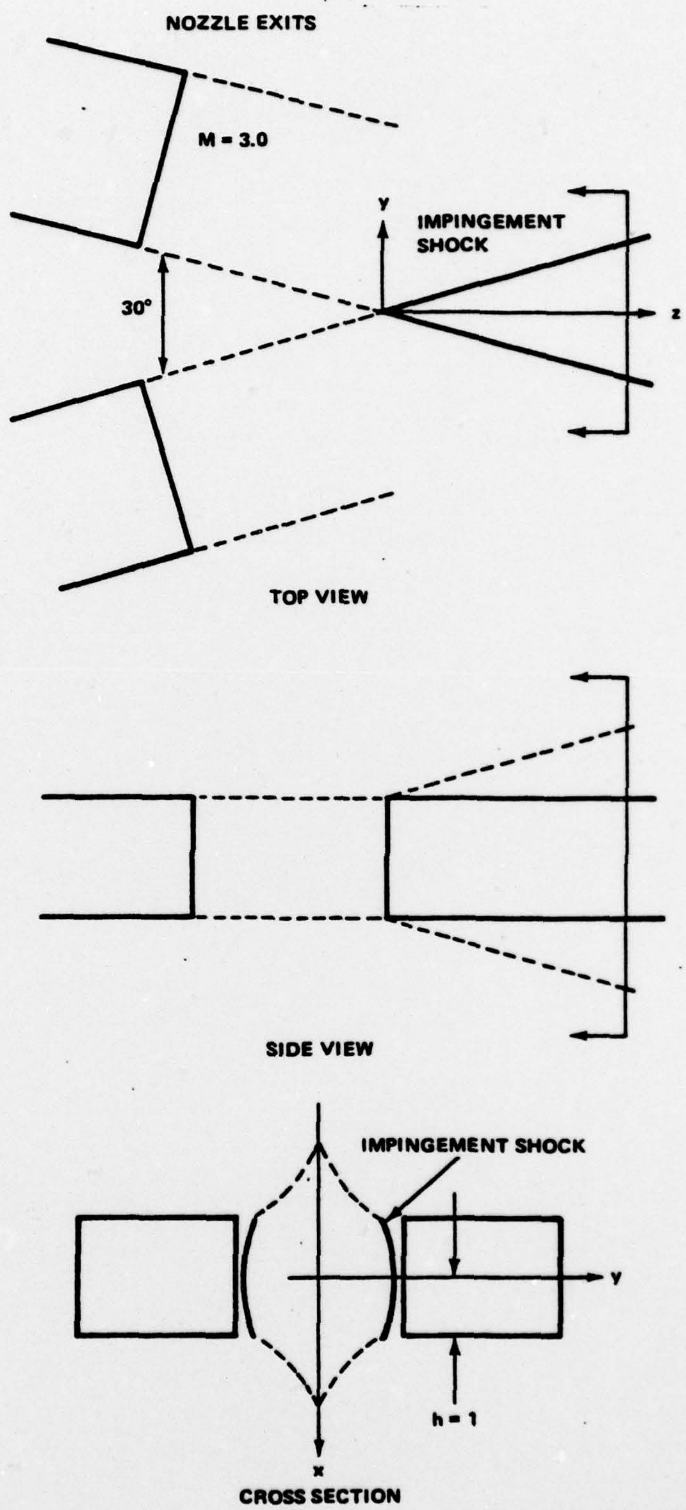

Fig. 6 Schematic of Geometry for the Impingement of Two Rectangular Plumes

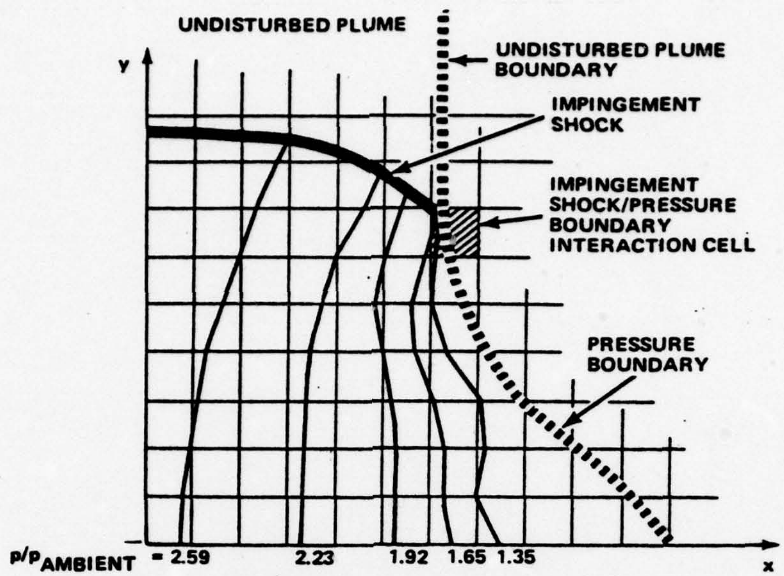

Fig. 7 Typical Cross Section at z = 2.12 Including Isobars for the Sample Calculation

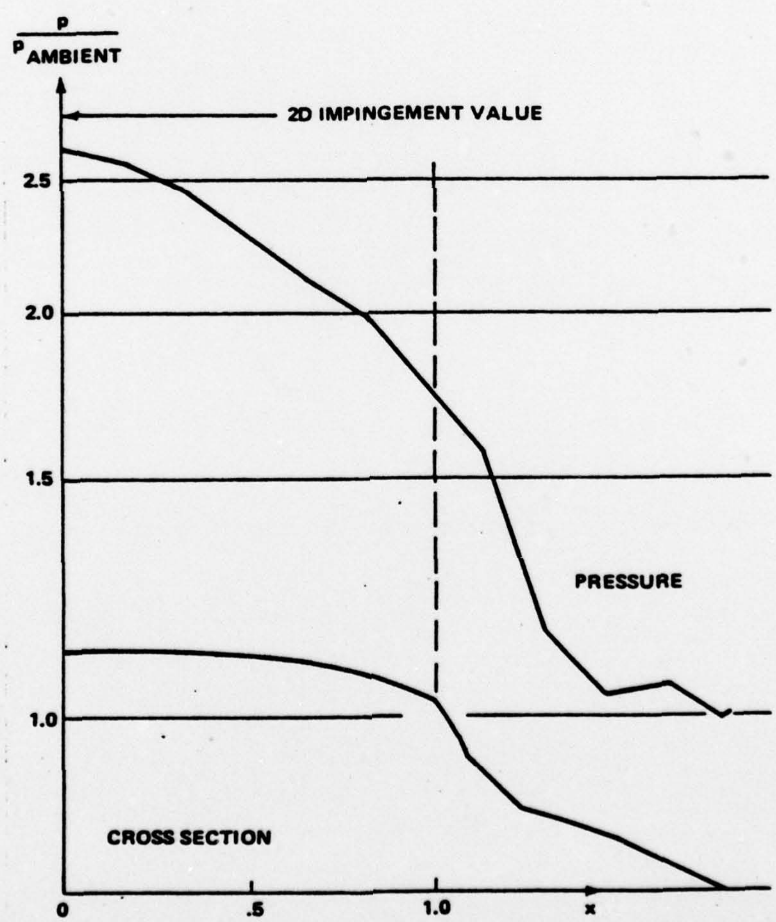

Fig. 8 Computed Symmetry Plane Pressure Profile z = 2.12

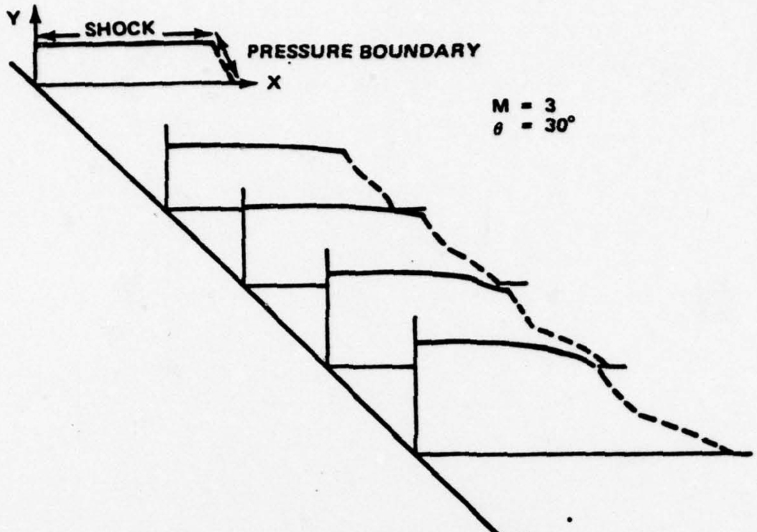

Fig. 9 Computed Development of the Flow Pattern for the Impingement of Two Rectangular Plumes

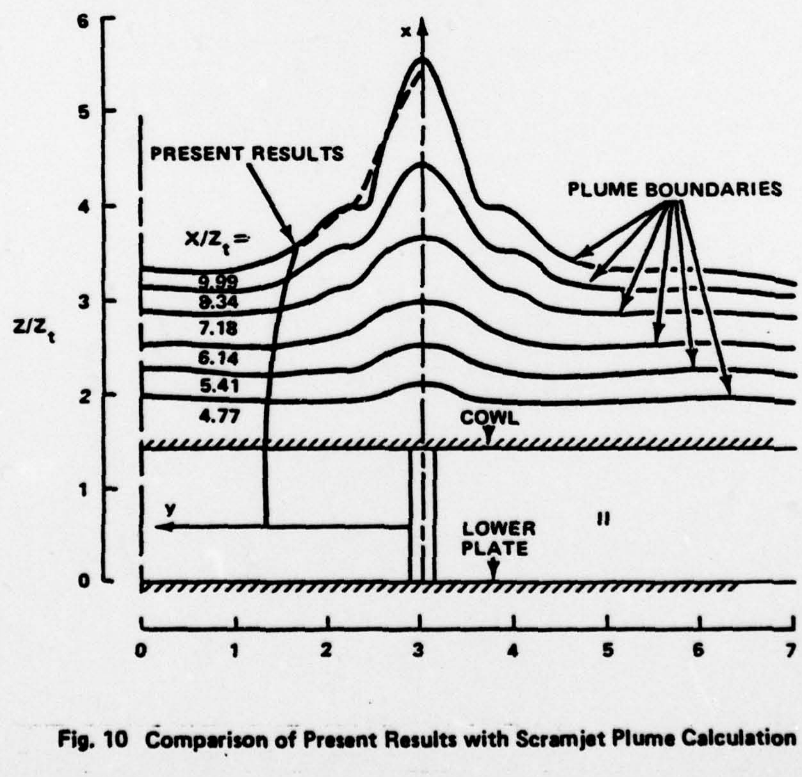

Fig. 10 Comparison of Present Results with Scramjet Plume Calculation

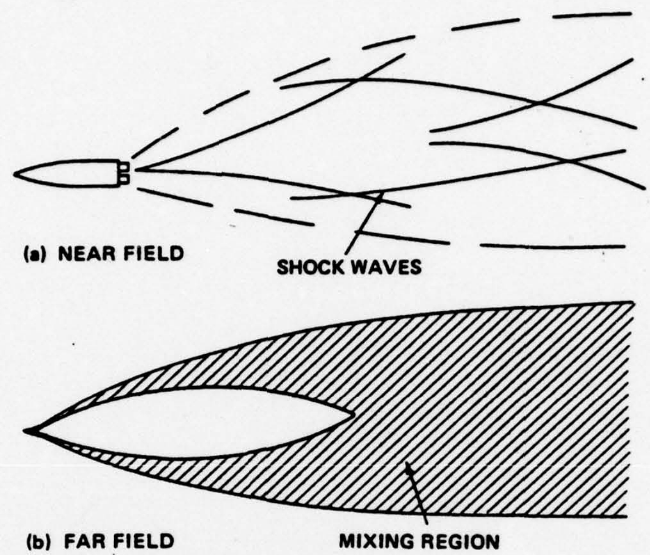

Fig. 11 Schematic of Near and Far Fields of a Rocket Plume

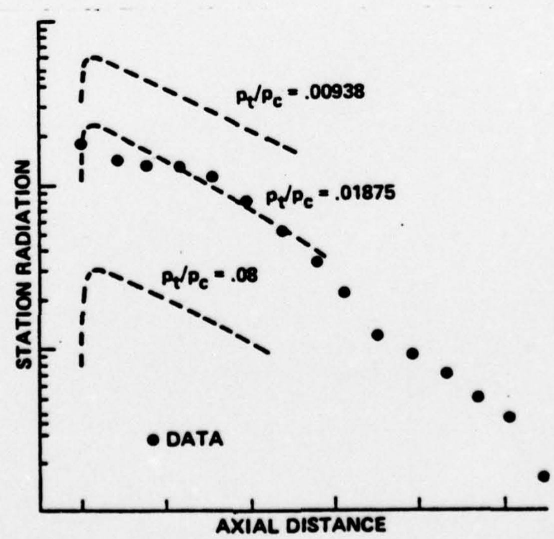

Fig. 12 Multiengined Missile Station Radiation at 50 KM Altitude

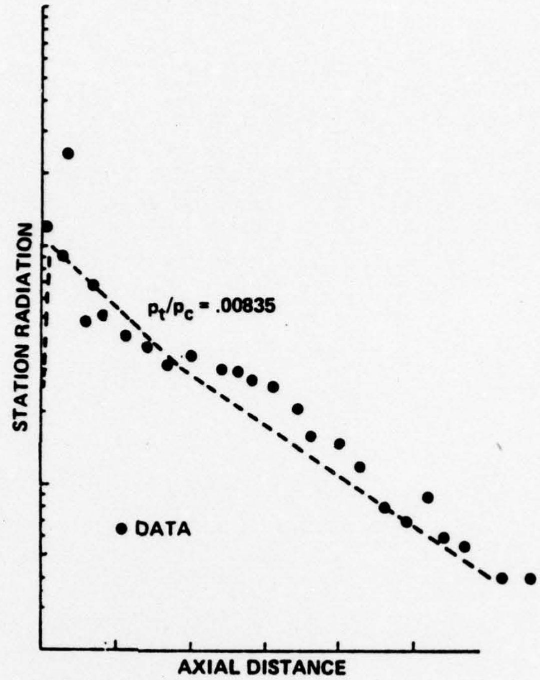

Fig. 13 Multiengine Missile Station Radiation at 60 KM Altitude

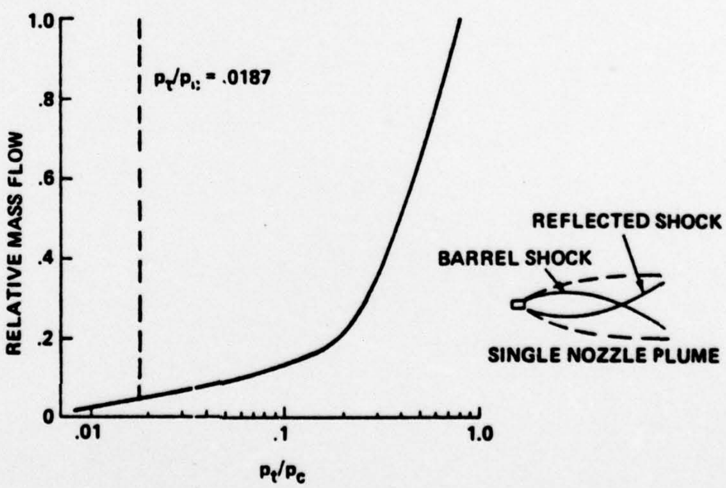

Fig. 14 Radial Distribution of Total Pressure Behind the Reflected Shock Wave for a Single Nozzle Plume

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Progress on the research effort "Analytical Investigation of Multinozzle Plume Flow Fields" includes major achievements such as ~~(a)~~ the development of numerical techniques and a computer code for calculation of the impingement of two rectangular plumes, and ~~(b)~~ a parametric study indicating that near field shock heating due to multiple nozzle flow field impingement can explain experimental data.

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